BASIC RESEARCH FROM THE HAYWIRED SCENARIO TO BETTER INFORM RESILIENCE PLANS

K.A. Porter¹

ABSTRACT

The USGS’s Science Application for Risk Reduction (SAFRR) program produced the ShakeOut, ARkStorm, Tsunami Scenario, and now HayWired—an earthquake planning scenario that reexamines a moment-magnitude (Mw) 7.0 Hayward Fault earthquake. Engineering aspects of past SAFRR scenarios have aimed for breadth over depth, but because several other research teams have already explored a Hayward Fault earthquake, we innovated in a few areas, aiming for depth over breadth. The earthquake engineering community already knows that a few older building types contribute disproportionately to societal risk in earthquakes, so we chose instead to use HayWired as a lens through which to examine ASCE 7-10’s seismic performance objectives for new buildings. We already know what ASCE 7-10’s authors think best serves the public’s needs for performance versus cost, so we carried out a scholarly human-subject survey that elicited the public’s preferences, which differ greatly from ASCE 7-10. People want more than they are getting. The earthquake resilience community has long urged people to protect themselves by doing drop, cover, and hold-on (DCHO), so we carried out another human-subject study to test how long it takes them (about 9 seconds) and how well they learn from the training material. The seismology community has been advocating for earthquake early warning (EEW) for many years, arguing among other things that EEW will improve life safety, so we used HayWired to quantify, for the first time, the number of injuries that can be avoided by combining EEW and DCHO (up to 1,500). We made basic advances in water resilience modeling, urban search and rescue, and other topics. ShakeOut, ARkStorm, the Tsunami scenario, and scenarios by other authors have raised people’s awareness of the importance of planning for disasters. More communities and businesses have decided to confront their natural-hazard risks. HayWired contributes with new research that will better inform those decisions.

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Introduction

Petroski [1] describes engineering innovation as partly a cycle of risk-taking, failure, and improvements to prevent future, similar failures. When it comes to natural disasters, those failures can be very costly in lives and money. Disaster planning scenarios can act as substitutes for actual disasters, allowing the engineer, planner, or community leader to learn from large, realistic, but hypothetical events, so that they can mitigate risk without having to wait for people to die first.

The USGS’s Science Application for Risk Reduction (SAFRR) program follows a long tradition of developing such scenarios. It produced the ShakeOut [2], ARrkStorm [3], and Tsunami Scenario [4], and now a new scenario called HayWired. The HayWired scenario describes an earthquake sequence that begins with a moment-magnitude (Mw) 7.0 rupture of the Hayward Fault in the East Bay part of the San Francisco Bay area in California. HayWired also includes a realistic aftershock sequence of 16 earthquakes of magnitudes of 5.0 and greater, the largest measuring Mw 6.4, located throughout the San Francisco Bay

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area. The earthquake’s fault rupture, seismic wave propagation, ground shaking, and secondary hazards such as liquefaction and landsliding are modeled using near-state-of-the-art methods by seismologists and geotechnical engineers of the U.S. Geological Survey and California Geological Survey. Earth-science aspects of the scenario were published in volume 1 of a 3-volume series [5]. Volume 2 presents some engineering impacts of the earthquake sequence [6].

Engineering aspects of past SAFRR scenarios have aimed for breadth over depth. ShakeOut for example included 18 special studies addressing various common or highly vulnerable building types and lifeline systems, comprising most though not all of the notable sources of damage or loss in the built environment. ShakeOut was unusual not in the scenario it examined—other researchers had hypothesized on the outcomes of a large rupture of the San Andreas Fault near Los Angeles—but in the number of experts and the diversity of topics it examined in detail. Approximately 300 experts ultimately contributed to the scenario. ARkStorm represents the first planning scenario of a large storm caused by an atmospheric river striking California. Its precipitation and flooding exceed anything in California’s written history, but resemble paleoflood evidence of 6 storms of the past 2 millennia. The SAFRR Tsunami Scenario similarly broke new ground in examining effects of a large hypothetical but realistic tsunami striking California.

HayWired is different from prior SAFRR scenarios. Several other research teams have already explored a Hayward Fault earthquake, e.g., [7], [8], and [9]. HayWired only briefly treats the well-known deficiencies of a few older building types that contribute disproportionately to societal risk in earthquakes— unreinforced masonry bearing wall buildings, nonductile concrete, and so on—and provides a fairly standard analysis using FEMA’s Hazus-MH software [10] to estimate the earthquake’s effects on the built environment. Unlike many previous disaster planning scenarios, SAFRR uses the HayWired scenario to innovate a few areas, producing new research and new knowledge, and aiming for depth over breadth.

**Engineering Research Innovations of the HayWired Scenario**

**Building Impairment in a Large Urban Earthquake Because of Risk-Targeted Seismic Design**

Luco et al. [11] show how one can set design-level shaking, which deals with strength and stiffness at that one level of shaking, to set an upper bound to probability that a new building will collapse during its design life, considering all levels of shaking that the building could experience and their exceedance rates. ASCE/SEI 7-10 [12], which sets seismic design requirements for the International Building Code [13], adopted Luco’s method. A new ordinary building (risk category II in the language of the International Building Code) designed using that method should have no more than a 1 percent probability of collapsing in an earthquake during its 50-year design life, albeit with potentially higher risk near large active faults.

In [14], HayWired is used as a lens through which to examine the seismic performance objectives for new buildings offered by ASCE/SEI 7-10. HayWired examines the effect of the risk-targeted design philosophy in terms of the overall impairment of a code-compliant building stock in a large urban earthquake. Such an earthquake can cause many buildings to collapse simultaneously, essentially calling in the debt of 1 percent collapse probability on hundreds of thousands of buildings simultaneously. FEMA P-695 [15] and its authors suggest that the expected value of collapse probability is somewhat lower than the upper bound—about 0.6 times the upper bound at MCER shaking. At least one expert [16] asserts that the ratio is more like 0.2 or 0.3, although the lower figure does not yet appear to have been published.

Taken together, Luco et al., ASCE/SEI 7-10, and FEMA P-695 offer a model of the collapse fragility among new buildings as a function of the ratio of earthquake shaking to shaking in the risk-targeted maximum considered event (MCER). That ratio is referred to here as the demand-to-design ratio, DDR. One can calculate DDR at any location in any given earthquake scenario by dividing the estimated scenario shaking by MCER shaking at that location. Evaluating the collapse fragility function at that level of DDR
provides the estimated collapse probability of a new building at that location in that earthquake. The product of the number of new buildings at that location and the collapse probability gives the expected value of the number of new, code-compliant collapsed buildings that would collapse at that location in that earthquake.

Furthermore [14] examines the effects of lesser damage that impairs buildings and makes them either unsafe to enter and occupy, or restricts their use to only portions of the building or to brief occupancy to retrieve one’s belongings. Five sources provide tallies of the number of collapsed buildings and the number of unsafe (red-tagged) building in the same geographic regions of the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake, which taken together suggest 13 buildings are rendered unsafe to enter and occupy for every building that collapses. Two sources give data sufficient to estimate the ratio of restricted-use buildings (yellow-tagged) to unsafe buildings (red-tagged) in California earthquakes: approximately 3.8:1. Multiplying the number of collapsed new buildings at any location by 13 gives the number of new buildings that would be red-tagged. Multiplying that number by 3.8 gives the expected value of the number of buildings that would be yellow-tagged. Taken together, these figures suggest that approximately 62 buildings are red-tagged or yellow-tagged for every collapsed building.

Figure 1A shows the outcomes in HayWired when all buildings meet current code requirements for new buildings, while Figure 1B shows outcomes if all buildings were 50 percent stronger than required for new risk-category II buildings. The figures show impairment rate, meaning the fraction of buildings that would collapse or be red- or yellow-tagged. Because the warm-colored areas in the maps are also areas of dense population, the left-hand map equates with about 24 percent of buildings in the 9 counties touching the San Francisco Bay being impaired. The right-hand map equates with about 6 percent impaired.

**Figure 1.** Fraction of buildings that would be impaired (collapsed, red- or yellow-tagged) following the HayWired mainshock, (A) if all buildings met current design requirements for risk-category II; or (B) if all buildings were 50 percent stronger than required for risk-category II.

**Public Preferences for the Seismic Performance of New, Code Compliant Buildings**

ASCE/SEI 7-10’s 1 percent collapse probability during the building’s design life grows in part from the observation by the authors of FEMA P-695 [15] that recent code-compliant design has up to a 10 percent probability of collapse at shaking associated with the maximum considered earthquake (MCE). Luco et al. [11] were essentially calibrating new design to achieve similar performance as recent code-
compliant design, but more uniformly in terms of long-term risk rather than collapse probability in a particular rare level of shaking. The implication—actually explicitly recommended in FEMA P-695—is that such a level of risk is societally acceptable.

To test that hypothesis, HayWired offers the first-ever scholarly human-subject survey to elicit public preferences for the performance of new, code-compliant buildings in a large urban earthquake [17]. The survey also examined the public’s preferences for tradeoffs between cost and impairment of the building stock, in terms of number of buildings that would remain habitable after such an earthquake. SAFRR carried out a web-based survey of 400 California adults and of 400 adults living in the Memphis TN and St Louis MO metropolitan statistical areas, asking respondents (among other things) what they believed the code’s seismic performance objectives were for new, code-compliant buildings, what the respondent thought the objective ought to be, and what the respondent thought people would pay to ensure that almost all buildings would remain habitable after a large, rare earthquake.

Survey results did not vary much between the two regions (California versus the central United States) or by the respondent’s household income or education. It turned out that relatively few respondents (about 25 percent) accurately understood that the building code largely aimed to ensure life safety, as opposed to ensuring with any specified level of confidence that buildings would be habitable or functional after rare shaking. The majority (about 59 percent) preferred that new buildings remain occupiable or functional after strong, rare shaking. And a majority (about 51 percent) expressed the belief that buyers should be willing to pay $3 or more per square foot to ensure that level of performance, a dollar figure that a related study [18] shows by several methods it would realistically cost. Most respondents (81 percent) felt that the issue of post-earthquake performance of new buildings was important or very important.

![Figure 2](image)

Figure 2. Responses of 800 adults from California and the St Louis MO and Memphis TN metropolitan statistical areas: (A) what they think the building code ensures for new buildings after strong, rare shaking; (B) what it should ensure; and (C) what post-earthquake occupiability is worth.

**Injury Prevention by Combining Earthquake Early Warning with Drop, Cover, and Hold On**

The earthquake resilience community has long urged people to protect themselves by doing drop, cover, and hold-on (DCHO). Since 2008, so-called ShakeOut drills have greatly increased DCHO training and exercise, reaching more than 57 million people worldwide in 2017 [19]. Expert consensus holds that DCHO can save lives and prevent injuries, but how many? At the same time, countries are developing earthquake early warning systems. In Japan for example, one can download and install a free Android or iOS app to one’s smart device that can provide several seconds of warning after an earthquake begins but before strong shaking reaches the user. In those seconds, one can begin and possibly complete DCHO, so
that one is better protected from many sources of injury before shaking even begins.

HayWired quantifies for the first time those benefits [20]. It offers a first-ever human-subjects study to quantify how long it takes people to complete DCHO actions after they have completed ShakeOut.org’s web-based training. The time appears to be approximately lognormally distributed with median of 8.8 sec and standard deviation of the natural logarithm of reaction time equal to 0.4, as shown in Fig. 3A. Eq. 1 sums over the affected region the number of injuries that would normally be caused by shaking at each location (denoted by $I_i$) with the fraction of people who could complete DCHO in the available warning time at each location (the lognormal cumulative distribution of DCHO reaction time, denoted by $F(t_i)$) and the fraction of injuries that could conceivably be avoided by completing DCHO (denoted by $f$). Fig. 3B illustrates HayWired warning times $t_i$ and population density. The result of the sum is approximately 1,500 nonfatal injuries avoided—an upper bound, given that it requires everybody to receive and quickly process and act on the EEW signal. Eq. 1 could be modified by factoring down the result by the fraction of people whom one could expect to receive and properly act on the EEW warning—an unknown quantity as of this writing, but a quantity that could in principle be estimated empirically.

$$B = \sum_{i=1}^{N} I_i \cdot F(t_i) \cdot f$$

Figure 3. (A) Time it took 487 adults to DCHO. (B) Population and HayWired warning time.

**A New Model of Water Network Resilience for Water System Engineers**

In [21], HayWired introduces basic advances in water resilience modeling. The work introduces a new model tentatively named CUWNet (University of Colorado Water Network Resilience) that offers this unique combination of features:

- Takes the system map (pipe segment materials, lengths, diameters, and midpoint locations) as inputs.
- Takes ground motions (shaking, landsliding, liquefaction, coseismic slip, and afterslip) as inputs.
- Provides model equations and parameters in a free report, not proprietary software.
- Can be implemented by a water engineer with only a geographic information system and spreadsheet.
- Treats the entire earthquake sequence, with shaking, liquefaction, landslide, coseismic slip, afterslip.
- Models lifeline interaction and resource limits such as limitations on fuel, telecom, crews, and supplies.
- Stochastic or deterministic mode, that is, one can explicitly model the probability distribution of all outcomes of interest, or more simply calculate expected values.
- Does not require a hydraulic analysis. This feature is both a strength and a weakness.
- Measures system performance in terms of damage, services available over time, and lost service-days.

The author applied CUWNet to two large Bay Area water distribution systems: those of East Bay Municipal Utility District (EBMUD) and of the San Jose Water Company (SJWC), both subjected to HayWired. The analysis suggests that EBMUD’s system could be so heavily damaged that 70 percent of its customers could lose water service. It could take 10 weeks to restore service to the average customer who initially loses service, and 6 months to restore the last customer. Outcomes are less severe though still substantial in HayWired for the newer and less strongly-shaken SJWC.

![Figure 4](image.png)

**Figure 4.** Restoration of two Bay Area water distribution system in the HayWired sequence: (A) EBMUD, and (B) SJWC.

In other work [22], the author offers initial model validation by estimating damage and restoration to the City of Napa’s water system in the August 2014 South Napa earthquake. CUWNet tends to agree with Napa’s actual experience, with almost all actual measures of damage and restoration falling within 1 standard deviation of their median values as estimated in 1,000 Monte Carlo simulations. The $M_w$ 6.0 South Napa earthquake, while significantly smaller than HayWired, nonetheless shook the epicentral region near Napa almost as strongly as the $M_w$ 7.0 HayWired mainshock would shake SJWC.

### A New Model of Urban Search and Rescue Needs in a Large Urban Earthquake

HayWired produced a new model of urban search and rescue (USAR) demands, quantifying USAR demands in terms of both victim extrication from collapsed buildings and demand for extrication of people trapped in elevators by a sudden power outage after an earthquake.

### Victim Extrication from Collapsed Portions of Buildings

To estimate the number of people in need of extrication from collapsed buildings, it is first necessary to estimate how many buildings would collapse in the earthquake and what fraction of their building area actually experiences the kind of collapse that could trap occupants. Surprisingly, no empirical or analytical model of either quantity seems to exist. Hazus-MH [10] estimates the probability that a given buildings will be in the complete structural damage state ($P_4$). It offers fixed estimates of the fraction of area of buildings in the complete structural damage state that collapses ($P_4$). But the product $P_4 \cdot P_5$ is not the probability that building has collapsed. If for example on average only a fraction $A$ of the square footage collapses, then the probability that a given building has at least some collapsed area (denoted here by $P_5$)
would be given by Eq. 2, and is larger than \( P_s \cdot P_c \) by a factor \( 1/A \). As used here, collapse means that elements of the vertical load resisting system lose their load-carrying capacity and elements that they support drop at least a little, even if the elements do not fall to the floor below. Figure 5 is an example of such collapse.

\[
P_s = (P_s \cdot P_c)/A
\]  

(2)

Figure 5. Image showing damage to older dwellings in the 1971 San Fernando, California, earthquake.

Eq. 3 gives the expected value of the number of people in a given building that require extrication from some collapsed area, denoted here by \( O_E \). In the equation, \( E \) is the fraction of occupants in the collapsed portion of a building who require USAR extrication and \( O \) is the total number of building occupants. Figure 5 shows that \( E \) is not necessarily equal to unity, because collapse does not necessarily mean that every place that experiences collapse turns into pockets of void spaces, that is, little closed cells with no exit.

\[
O_E = P_s \cdot P_c \cdot E \cdot O
\]  

(3)

Other resources never quite provide the probability that any given existing building experiences some collapse, e.g., ATC-13 [23] and FEMA P-695 [15]. Neither gives factors \( A \) or \( E \). To estimate them, the author examined every photograph in the NISEE database [24] that shows earthquake-induced collapse of a California building of the past 50 years [25] and estimated the apparent building type, \( A \), and \( E \).

<table>
<thead>
<tr>
<th>Material</th>
<th>Count</th>
<th>Average A</th>
<th>Average E</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>73</td>
<td>23%</td>
<td>0.66</td>
</tr>
<tr>
<td>Tilt-up concrete</td>
<td>14</td>
<td>17%</td>
<td>0.10</td>
</tr>
<tr>
<td>Other concrete</td>
<td>9</td>
<td>50%</td>
<td>0.94</td>
</tr>
<tr>
<td>Unreinforced masonry</td>
<td>18</td>
<td>28%</td>
<td>0.98</td>
</tr>
<tr>
<td>Wood</td>
<td>32</td>
<td>17%</td>
<td>0.66</td>
</tr>
<tr>
<td>All except unreinforced masonry</td>
<td>54</td>
<td>22%</td>
<td>0.56</td>
</tr>
<tr>
<td>All except chimneys</td>
<td>66</td>
<td>25%</td>
<td>0.65</td>
</tr>
</tbody>
</table>

**Table 1.** Average affected area (A) and average fraction of occupants in collapsed areas requiring extrication (E) in the urban search and rescue (USAR) model.

**Victim Extrication from Stalled Elevators**

As part of his study of elevator damage in the ShakeOut scenario, Schiff [26] suggested that many people could be trapped in stalled elevators between floors when an earthquake occurs, because older elevators generally lack emergency power and because loss of electricity can reach an elevator long before seismic
waves trigger its safety devices. HayWired follows up on that possibility by quantifying the number of elevators in a metropolitan region, the fraction of them that would be occupied and in motion between floors at a given time on a workday afternoon, and the fraction of those that would lack emergency power.

In [25], the author suggests estimating the number of elevators in motion with people inside and no emergency power (denoted $V_0$) using Eq. 4 and the number of people trapped in elevators (denoted $N_e$) using Eq. 5. In the equations, $P_m$ is the population of the area, $p$ is the average number of people per elevator, $f_b$ denotes the fraction of elevators with emergency power, $f_o$ is the estimated fraction of all elevators that are in use at the time of the earthquake, $f_c$ is the fraction of the time that an elevator that is currently in use with passengers in it is traveling between floors with the doors closed, and $d$ denotes the average number of passengers per occupied elevator. Parameter values are drawn from a real estate database, a textbook on the design of vertical transport within buildings, and advice of an elevator consultant.

\[
V_0 = \left( \frac{P_m}{p} \right) \cdot f_o \cdot f_c \cdot (1 - f_b) \quad (4)
\]

\[
N_e = \left( \frac{P_m}{p} \right) \cdot f_o \cdot f_c \cdot (1 - f_b) \cdot d \quad (5)
\]

Applying Eq. 2 through 5, the author estimates 22,000 people could be trapped in 4,500 elevators by the sudden loss of electricity after the HayWired mainshock and require USAR assistance. In addition, 2,400 people are trapped in 5,000 collapsed buildings, requiring USAR extrication (some buildings collapse without trapping occupants). Resilience measures could reduce both figures; see [25] for details.

**Conclusions**

Scenarios by SAFRR and by other authors have raised people’s awareness of the importance of planning for disasters. Many communities and businesses have undertaken to manage their natural-hazard risks. HayWired contributes with new research to better inform those decisions with new models of:

- Unforeseen effects of the building code’s seismic performance objectives for new, risk-category II buildings. One effect is a disturbingly large fraction of a code-compliant building stock (24 percent) that can be impaired in a large metropolitan earthquake.
- Public preferences and willingness to pay for the seismic performance of new buildings. People seem to prefer much better performance from new buildings than the building code aims to provide.
- The potential for earthquake early warning with drop, cover, and hold on to reduce earthquake injuries. In HayWired, up to 1,500 injuries could be avoided.
- A new model of water network resilience for use by water-system engineers that estimates damage and recovery in terms of service-days lost, using only spreadsheet and a geographic information system. The model has been validated in a limited way by application to the 2014 South Napa earthquake. The model estimates that it will take up to 6 months to restore water service in one system.
- A new model of urban search and rescue to estimate demands for extricating people trapped in stalled elevators or collapsed buildings. HayWired could trap 22,000 people in 4,500 stalled elevators, and 2,400 more in 5,000 collapsed buildings.

**Acknowledgments**

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